NUCLEAR SCIENCE AND TECHNIQUES **25**, 040401 (2014)

Tokamak fusion neutron spectrometer based on PXI bus*

JIANG Xiao-Fei (蒋小菲),[1,2] CAO Jing (曹靖),[1,2] JIANG Chun-Yu (蒋春雨),[1,2] CAO Hong-Rui (曹宏睿),[1,2,†] SONG Xian-Ying (宋先瑛),[3] and YIN Ze-Jie (阴泽杰)[1,2]

[1] *State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei 230026, China*

[2] *Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China*

[3] *Southwestern Institute of Physics, Chengdu 610041, China*

(Received November 13, 2013; accepted in revised form March 3, 2014; published online July 17, 2014)

In order to realize on-line real-time measurement of dynamic and time-sharing neutron spectrum of HL-2A, a tokamak fusion neutron spectrometer based on PXI bus was developed. It consists of electronics system and eight thermal neutron detectors, namely SP9 ^{3}He proportional counter, embedded in eight polyethylene spheres in different diameters. Response function of the eight polyethylene spheres was the key to calculate the neutron spectrum accurately. In this paper, response function of the eight polyethylene spheres is simulated by adopting Geant4 code, and neutron counts from an ^{241}Am-Be neutron source are measured by the eight detectors. The calculated spectrum of the Am-Be neutron is accurate in 0–2 MeV region, and is similar to the theoretical spectrum. The tokamak fusion neutron spectrometer was used in HL-2A device to monitor the dynamic neutron spectrum of HL-2A on-line and real-time.

Keywords: HL-2A, Response function, Calibration, Dynamic time-sharing energy spectrum, ^{241}Am-Be

DOI: 10.13538/j.1001-8042/nst.25.040401

I. INTRODUCTION

HL-2A [1, 2] is a tokamak fusion experiment device of China, which laid the foundation of advanced tokamak physics experiment and the research of ITER and fusion reactor. HL-2A presented many challenges for fusion neutron spectrum measurements. One of the major difficulties is on-line and real-time measurement of the dynamic and time-sharing fusion neutron spectrum. In this regards, we developed a tokamak fusion neutron spectrometer based on PXI bus. It consists of an electronics system and eight thermal neutron detectors, namely SP9 ^{3}He proportional counters embedded in eight polyethylene (PE) spheres of different diameters. The neutron spectrometer uploaded eight time-sharing neutron counts to the system controller of PXI chassis through PXI bus. The detectors and electronics will be finally activated by neutrons in the fusion reactor.

As a common radioactive neutron source used in laboratory, an ^{241}Am-Be neutron source is featured by its small size, long term use, simple protection, and stable neutron emission. Activity of the neutron source at any time can be calculated accurately according to the half-lives of radionuclide decay. Spectrum measurement of the Am-Be neutron source can verify the tokamak fusion neutron spectrometer, without activating the detectors and electronics by fusion neutrons. Response functions of the PE spheres are the key to calculating neutron spectrum accurately. In this paper, response functions of the eight PE spheres are simulated by the Geant4 code, and neutron spectra of an Am-Be neutron source are measured.

II. PRINCIPLE OF MEASUREMENT

The eight PE sphere spectrometers are of 4, 5, 6, 7, 8, 9, 10, and 12 inches in outer diameter, respectively. An SP9 ^{3}He proportional counter of 33-mm outer diameter is located in each of the sphere center. This kind of counters is usually used for thermal neutron measurement because of larger reaction cross sections [3] and lower γ sensitivity.

Assuming the following parameters: m, number of PE spheres in different diameters; $R_i(E)$, the response function of the i^{th} sphere [4, 5]; $\Phi(E)$, the fluence of neutrons in different energies, and $N_1, \cdots, N_m$, counts of the PE spheres, then the i^{th} sphere will have:

$$N_i = \int \Phi(E) R_i(E) \mathrm{d}E. \tag{1}$$

Neutron spectrum measurements are finally converted into calculating the linear equation of

$$R(E)\Phi(E) = N, \tag{2}$$

where, $R(E)$ is the coefficient matrix about response function, N is the data of eight measurements, and $\Phi(E)$ is the neutron spectrum. N_i can be experimentally obtained, while the response function $R_i(E)$ can be obtained by Geant4 simulation. So, simulation of response function is the key to calculating the spectrum of Am-Be neutron source.

A block diagram of the fusion neutron spectrometer based on PXI bus is shown in Fig. 1. It consists of eight detector/pre-amplifier/main-amplifier, and system controller of PXI chassis. The charge-sensitive pre-amplifiers use NIM

* Supported by Ministry of science and technology major projects (No. 2013GB104003), National Natural Science Foundation of China (No. 11375195), Ministry of Education and Youth Innovation Fund (No. WK2030040037)

† Corresponding author, caohr@ustc.edu.cn

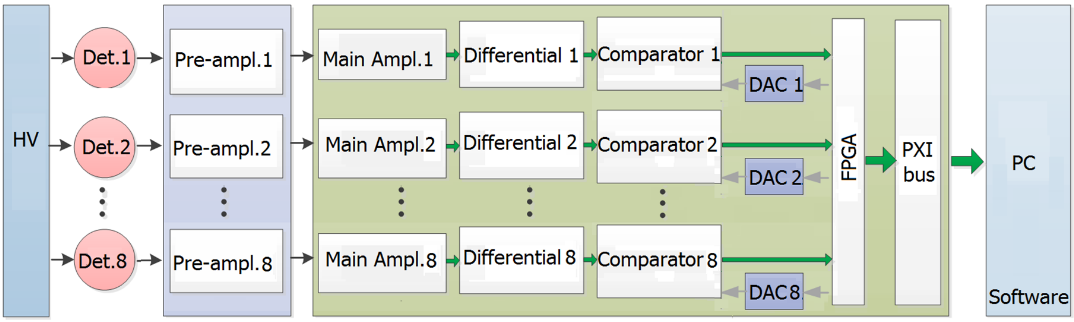

Fig. 1. (Color online) System block diagram of the tokamak fusion neutron spectrometer based on PXI bus.

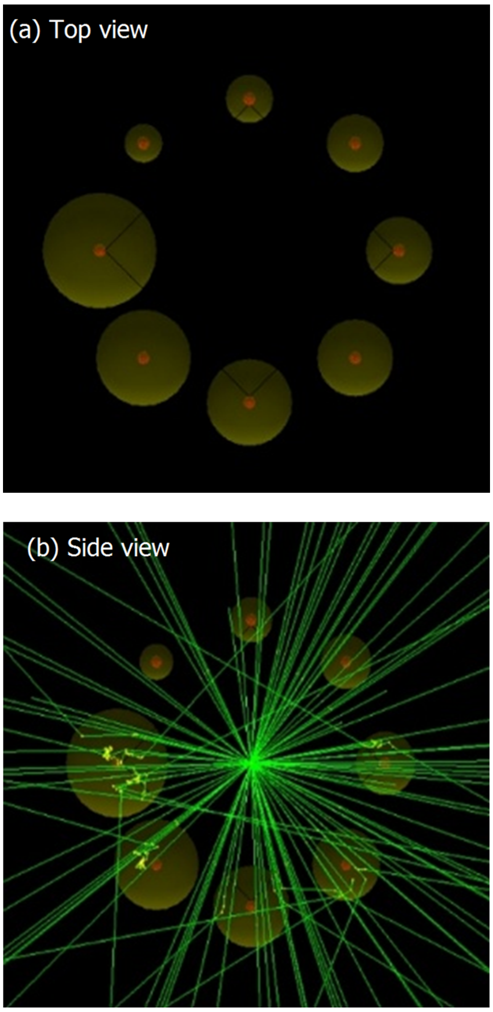

Fig. 2. (Color online) Schematics of the Geant4 simulation.

chassis and the main electronics use PXI chassis. The detector signals amplified by the pre-amplifier are amplified, shaped and filtered by the main electronics. The DACs output the upper and lower thresholds to the comparator through the FPGA. The comparators compare the main amplifier output with the upper and lower thresholds, and the FPGA processes the comparison results. The FPGA uploads eight time-sharing neutron counts to the system controller of PXI chassis through PXI bus. The system controller works out and displays real-time neutron spectrum.

By measuring counts of the eight PF spheres simulating the response function, and using Eq. (2), spectrum of the Am-Be neutron source can be calculated.

III. GEANT4 SIMULATION

The Geant4 simulation of response function is shown schematically in Fig. 2 [6–8], with eight PE spheres of different diameters (yellow colored) and the neutron source in the center. The red dots in the spheres are eight embedded SP9 ^{3}He proportional counters. The SP9 ^{3}He counter is 40 cm from the neutron source. The neutrons are emitted in 4π solid angle in the simulation.

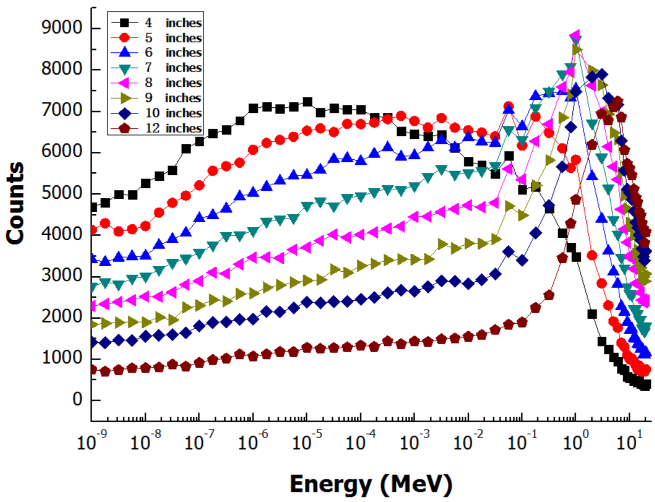

Fig. 3. (Color online) Response function of the eight PE spheres of Φ 4 inches to Φ 12 inches.

The fast neutrons are slowed down to thermal neutrons by elastic collisions with hydrogen atoms or carbon atoms. For the PE spheres of small diameters of PS, low energy neutrons after moderating shall have great chance to reach the detector in the sphere center, while high energy neutrons after moderating are likely to escape. For the PE spheres of large diam-

Fig. 4. (Color online) Experimental measurement environment.

eters, a large number of low energy neutrons are absorbed in the moderation, while thermal neutrons being slowed down from high energy neutrons shall reach the detector. Neutrons in different energies are moderated in different degrees in the PE spheres of different diameters. The response functions simulated by Geant4 are shown in Fig. 3. The response functions are peaked in the low energy region for smaller diameter PS (e.g. 4 inches), but the peak position moves toward the high energy region as the sphere diameter increases. The influence of neutrons escaped from the small PE spheres and scattered from the floor, should be considered.

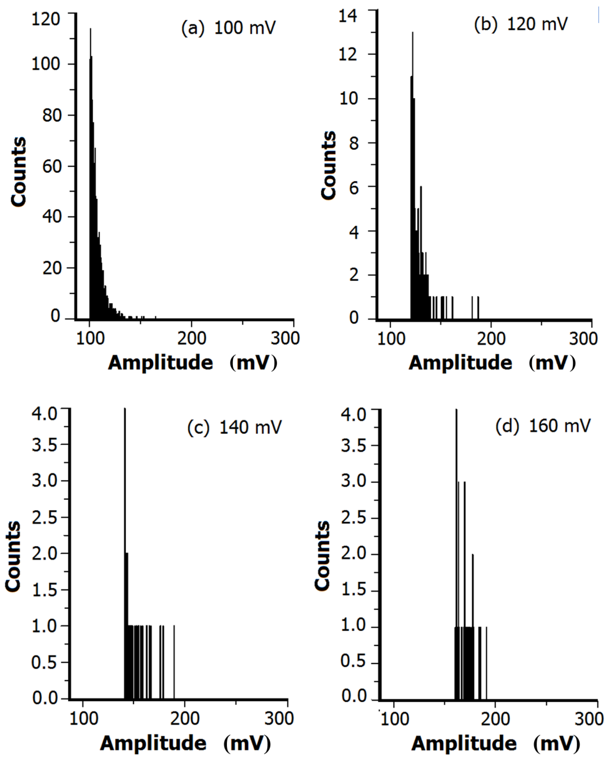

Fig. 5. Background counts of Tokamak fusion neutron spectrometer, at the low threshold of 100–160 mV.

IV. EXPERIMENTAL MEASUREMENT

The experiment was designed to calibrate [9] the response function simulated by Geant4 and verify the tokamak fusion neutron spectrometer. An Am-Be neutron source [10, 11] was used. Placement of the eight PE spheres (Fig. 4) was consistent with simulation. The fusion neutron spectrometer identifies the neutron signals through amplitude. As described in Sec. II, the signal amplitude between the lower and upper thresholds is neutron signal, and the count N_i adds one. There is always noise in an electronics system. To avoid the noise influence, the lower threshold must be higher than most of the noise.

The background counts without a neutron source can be obtained by setting a lower threshold. Fig. 5 shows background counts at lower thresholds of 100 mV, 120 mV, 140 mV and 160 mV. It can be seen that the background counts are very small at lower threshold of $\geq$ 140 mV. So, the lower threshold for the neutron source is 140 mV.

With the lower threshold of 140 mV and the upper threshold of 500 mV, the counts of 9-inch PE sphere detecting the Am-Be neutron source is shown in Fig. 6.

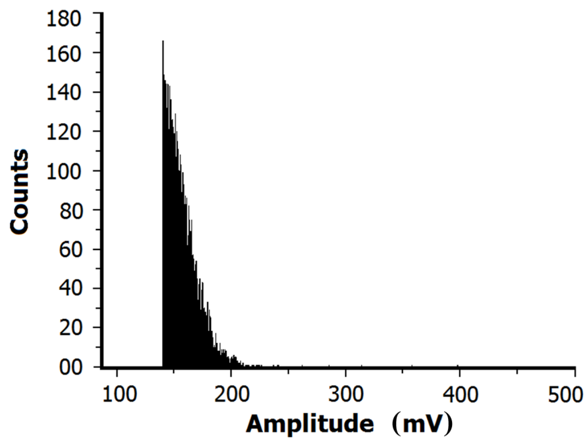

Fig. 6. ^{241}Am-Be neutron source counts of the 9-inch PE sphere, at 140 mV low threshold.

Using the ^{241}Am-Be neutron source, the time-sharing counts of the PE spheres in diameters of 4, 5, 6, 7, 8, 9, 10 and 12 inches were measured as $N_i = 534, 1077, 1161, 1717, 1768, 2367, 1959$ and 662, respectively. Combined with the simulated response function, the Am-Be neutron source spectrum was calculated with Eq. (2), as shown in Fig. 7. The black squares are the theoretical results in Ref. [12], and the red dots are the calculated spectrum with the response function and measured data.

It can be seen that the calculated spectrum of Am-Be neutron is accurate in the 0–2 MeV region, but in high energy region, relative errors of the calculated spectrum are large. This is because of neutron scattering from the floor. The calculated spectrum of Am-Be neutron is similar to the theoretical spectrum. The experimental results show that the response function can be simulated by Geant4 for the tokamak fusion neutron spectrometer to monitor the dynamic and time-sharing

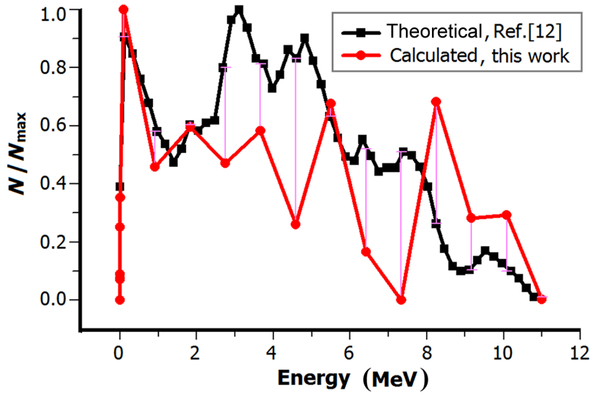

Fig. 7. (Color online) Spectrum of the Am-Be neutron source.

neutron energy spectrum on-line and real-time.

V. CONCLUSION

The fusion neutron spectrometer, with eight time-sharing neutron counters connected to the system controller of PXI chassis through PXI bus, was developed to monitor spectrum of the tokamak fusion neutrons. The response function of the eight PE spheres was simulated by adopting software Geant4. The experiment using Am-Be neutron source to verify the simulated response function was performed. The calculated spectrum of Am-Be neutron is accurate at 0–2 MeV region. The calculated spectrum of Am-Be neutron is similar to the theoretical spectrum. The experiment verifies the response function simulated by Geant4 and the tokamak fusion neutron spectrometer. The tokamak fusion neutron spectrometer was used in HL-2A device to monitor the dynamic neutron spectrum of HL-2A on-line and real-time.

[1] Zhang X, Yuan X, Xie X F. Nucl Instrum Meth A, 2012, **687**: 7–13.
[2] Yanga Y, Maruyama S, Pitts R, *et al*. Fusion Eng Des, 2010, **85**: 2292–2294.
[3] Alevra A V and Thomas D J. Radiat Prot Dosim, 2003, **107**: 37–72.
[4] Thomas D J and Alevra A V. Nucl Instrum Meth A, 2002, **476**: 12–20.
[5] Ogata T, Kudo S, Watanabe Y, *et al*. Radiat Prot Dosim, 2011, **146**: 107–110.
[6] Pioch C, Mares V, Rühm W, *et al*. Radiat Meas, 2010, **45**: 1263–1267.
[7] Allison J, Amako K, Apostolakis J, *et al*. IEEE T Nucl Sci, 2006, **53**: 270–278.
[8] Prokopovich D A, Reinhard M I, Cornelius I M, *et al*. Radiat Prot Dosim, 2010, **141**: 106–113.
[9] Howell R M, Burgett E A, Wiegel B, *et al*. Radiat Meas, 2010, **45**: 1233–1237.
[10] Chatterjee S, Bakshi A K, Tripathy S P. Nucl Instrum Meth B, 2010, **268**: 2825–2830.
[11] Vega-Carrillo H R, Manzanares-Acuña E, Becerra-Ferreiro A M, *et al*. Appl Radiat Isotopes, 2002, **57**: 167–170.
[12] IAEA. Compendium of neutron spectra and detector responses for radiation protection purposes, Technical reports series 403, International Atomic Energy Agency, Vienna, Austria, 2001.